

DRIFT AND OBSERVATIONS IN COSMIC-RAY MODULATION. I.

M. S. Potgieter¹Space Science Center, University of New Hampshire,
Durham, NH 03824, USA1. Introduction

Gradient and curvature drift, which are explicitly contained in standard cosmic-ray transport theories, were neglected until the mid-1970's. It was then realized that the sector structure of the interplanetary magnetic field (IMF) observed in the ecliptic plane does not pervade the whole heliosphere (e.g., Smith et al., 1978), but has a topology corresponding closely to that of a dipole at the Sun. Since then, several drift models based on the numerical solution of the cosmic-ray transport equation were published (Jokipii and Kopriva, 1979; Kota and Jokipii, 1983, and references therein). These models, mostly concerned with proton modulation, illustrate the general features of drift and show that drift has a rather dominant effect on solutions over a wide range of parameters.

The independently developed drift model of Potgieter and Moraal (1983, 1985) in general confirms these results, according to which the four basic effects - convection, diffusion, drift and energy change - each contribute to the modulation of cosmic rays in the heliosphere. The relative importance of drift has, however, not yet been established. In order to do so, observational evidence of effects primarily dependent on drift are required.

The change in polarity of the large-scale IMF is of fundamental importance in drift models. A major implication of this reversal in polarity is that protons and electrons should, due to drift, exhibit different behavior during consecutive solar activity cycles. A charge-sign dependent effect should therefore be observable, the magnitude of which may indicate the relative contribution of drift to the modulation of cosmic rays.

In this paper we report on our investigation of this effect using observed solar minimum spectra (Webber et al., 1983) and on the change in phase and amplitude of the diurnal anisotropy observed after the IMF polarity reversals in 1969-71 and 1980 (Potgieter and Moraal, 1983).

2. Model Calculations

We solved the steady-state transport equation numerically assuming azimuthal symmetry. The solar wind is assumed to increase rapidly as a function of radial distance r to 400 km s^{-1} in a spherical heliosphere with an outer boundary at $r_b = 50 \text{ AU}$. The interstellar input spectra, boundary conditions, the spatial and energy dependence of the diffusion coefficients are given and motivated by Potgieter and Moraal (1985).

The IMF is assumed an Archimedean spiral with reversal of polarity across a flat neutral sheet. The reversal can be made either abrupt or smooth using a transition parameter $\theta_{\perp} = 90^\circ$ and $85^\circ < \theta_{\perp} < 90^\circ$ respectively. The drift velocity field calculated with $\theta_{\perp} = 86^\circ$ is schematically presented for protons in Fig. 1.

¹ Also: Dept. of Physics, Potchefstroom University, South Africa

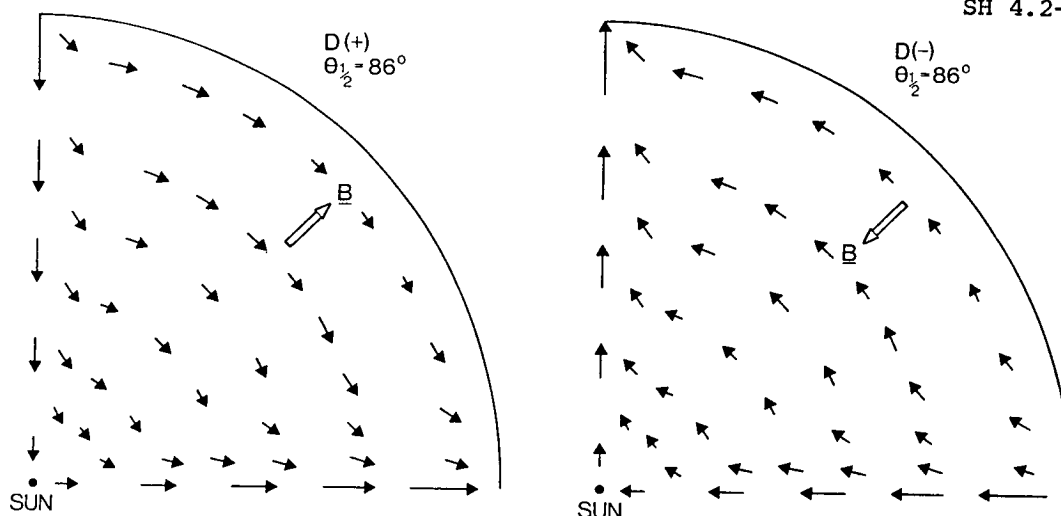


Fig. 1: Drift velocities for protons in the meridional plane with the transition parameter $\theta_1 = 86^\circ$. D(+): $\sim 1970-1980$. D(-): $\sim 1959-1970$; 1980-1991. The drift velocities reverse direction for electrons.

According to Fig. 1 positively charged particles are transported from the polar regions to the inner heliosphere during the D(+) epoch (including 1976-77) but from the outer equatorial regions to the inner heliosphere during the D(-) epoch (including 1965). This effect is quantitatively illustrated in Fig. 2 of Part 2 (Paper SH4.2-5). In contrast with the no-drift case, protons and electrons reaching Earth should traverse different regions of the heliosphere during consecutive solar minimum periods, causing a charge-sign dependent effect.

3. Results and Discussion

No-drift models have become less successful to simultaneously fit proton and electron spectra observed before and after IMF polarity reversals, e.g., the 1965 and 1977 spectra (Evenson et al., 1983). This indicates that the detailed behavior of low energy electrons and protons cannot be fully understood within the framework of numerical solutions to the spherically symmetric transport equation (see e.g., Rockstroh, 1977).

Recently, Evenson and Meyer (1984) reported that although protons and electrons responded to the onset of less modulation in much the same way in 1981-82, there is a systematic difference between the two sets of data. The electrons recovered more rapidly than the protons and were not as strongly modulated with increased activity in late 1982. Moreover, this effect is totally different from that observed by Burger and Swanenburg (1973) in 1968-72 when the electron recovery lagged behind that of protons. Perko (1984) used a time-dependent spherically symmetric model, doing calculations for an entire solar cycle, to establish to what extent the difference in rigidity between the data sets of Evenson and Meyer could produce the observed hysteresis. He found that the hysteresis went in the sense of the Burger-Swanenburg data. No-drift models can therefore neither explain the observed effect nor the higher electron intensities, but lower proton intensities observed in 1965 compared to that observed in 1976-77.

Our model, based on the assumption of steady-state and a flat neutral sheet, is applicable only to periods of minimum solar activity. This is, however, also the time for the best ordered, large-scale IMF and the most likely period for drifts to occur. We therefore concentrated on a simultaneous fit to the observed 1965 and 1977 proton and electron spectra compiled by Evenson et al. (1983).

In contrast with the no-drift models, we could fit the mentioned spectra using one single set of modulation parameters, except for a change in the polarity of the IMF. Our result is best illustrated when compared to the ratio of the 1977 and 1965-66 data for protons and electrons respectively (Webber, et al., 1983). This is shown in Fig. 2.

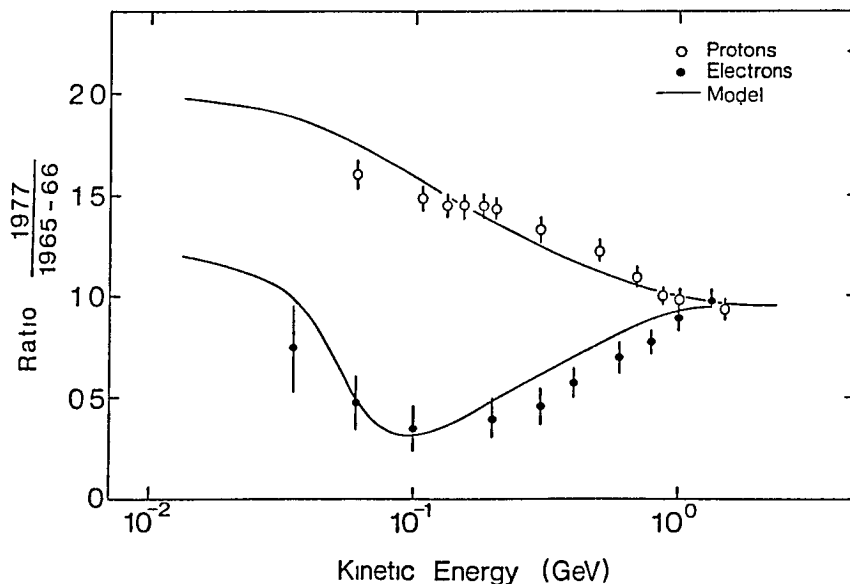


Fig. 2: Drift model calculations compared to proton and electron ratios for 1977 relative to 1965-66 (Webber, et al., 1983). The parameters used are given by Potgieter and Moraal (1985).

We want to emphasize that, other than perhaps less sophisticated equipment, there is no reason to doubt the validity of the 1965-66 electron data (Webber, private communication). We therefore interpret the result of Fig. 2 as a charge dependent effect due to drift, causing a factor of ~ 2 difference at 500 MeV between consecutive solar minimum electron spectra.

An observation which is also unambiguously related to the reversal of the IMF polarity, is the shift in phase and amplitude of the diurnal anisotropy observed in 1969-71 and again in 1980-81 (Swinson, 1983). Fig. 3 shows, on a harmonic dial, the observed geomagnetically corrected anisotropy vector, calculated from the diurnal variation in the Hermanus neutron monitor (4.55 GV) counting rate. The vectors are averaged for 1964-66 and 1975-77; also for the entire period between polarity reversals, i.e., 1959-70 and 1971-79 respectively. These are compared to the calculated anisotropies at 1 GeV, using the same single set of modulation parameters used in Fig. 2. Our model is at least consistent with the observed shift in both phase and amplitude of the diurnal anisotropy following the 1969-71 polarity reversal, an effect which cannot be simulated by conventional spherically symmetric models.

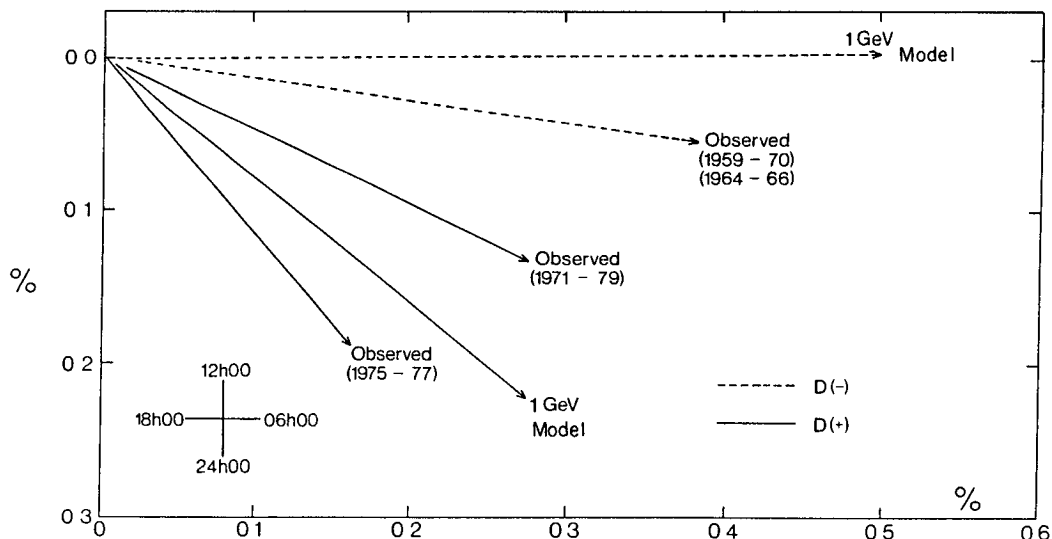


Fig. 3: The observed diurnal anisotropy (Hermanus, 4.55 GV), compared to the computed anisotropy vectors at 1 GeV. The observed values are averaged for the time periods indicated.

4. Summary and Conclusions

We have illustrated that a relative simple drift model can, in contrast with no-drift models, simultaneously fit proton and electron spectra observed in 1965-66 and 1977, using a single set of modulation parameters except for a change in the IMF polarity. We interpret this result, together with the observation of Evenson and Meyer (1984) that electrons are recovering more rapidly than protons after 1980, in contrast with what Burger and Swanenburg (1973) observed in 1968-72, as a charge-sign dependent effect due to the occurrence of drift in cosmic-ray modulation. The same set of parameters produces a shift in the phase and amplitude of the diurnal anisotropy vector, consistent with observations in 1969-71 and 1980-81.

5. Acknowledgements

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